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THESIS

FINAL MODIFICATIONS OF NPS
***HUMMINGBIRD* REMOTELY PILOTED**
HELICOPTER IN PREPARATION
FOR FLIGHT

by

Andrew J. Booth

December, 1995

Thesis Advisor: E. Roberts Wood

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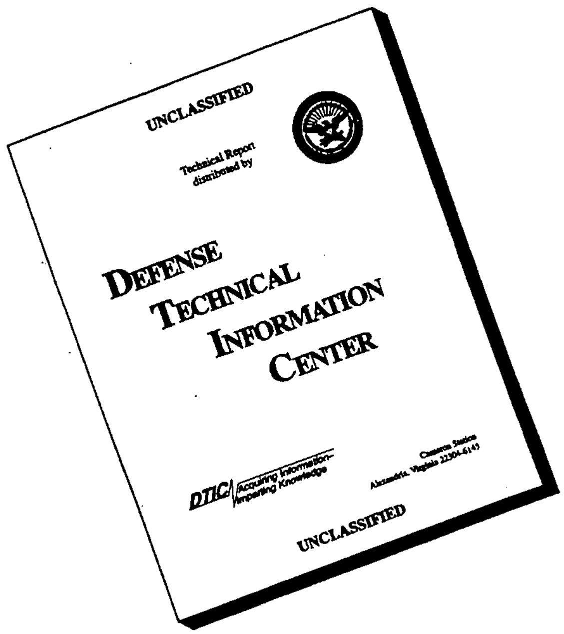

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The goals of this thesis were to make final design modifications and perform static testing to prepare the *Hummingbird*, a 150 pound, remotely piloted helicopter (RPH), for untethered flight. The major elements involved were: (1) The adaptation of a suitable, permanently-dedicated test stand for use with large-scale RPH/RPV (remotely piloted vehicle) aircraft; (2) A major rotor drivetrain improvement to the helicopter to enable it to autorotate and safely land in the event of an in-flight engine failure, thus avoiding potential loss of the helicopter due to crash; (3) Complete break-in and testing of a replacement engine for a mechanically-seized first engine; and (4) Limited hover testing while secured to the tether test stand.

Test stand modifications include design and implementation of a compression spring to offset the weight of the new mounting assembly and a restricting collar to confine mobility of the stand's universal joint. The mechanical change to the drivetrain consists of replacement of a conventional belt-drive sprocket with a one-way sprague clutch bearing inside the gear. This provides the Hummingbird with the critical capability to autorotate. The new engine, correctly broken in, and the subsequent static testing provide the Department of Aeronautics and Astronautics with an operational platform ready to perform subsequent in-flight testing.

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FINAL MODIFICATIONS OF NPS *HUMMINGBIRD*
REMOTELY PILOTED HELICOPTER
IN PREPARATION FOR FLIGHT

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of the requirements for the degree of

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I. INTRODUCTION

To provide a platform to facilitate research involving rotorcraft technologies, the Department of Aeronautics and Astronautics at the Naval Postgraduate School elected to procure a remotely piloted helicopter (RPH). After evaluating whether to design and fabricate one on the premises or to purchase an aircraft from an external source, the unassembled *Hummingbird* RPH, with an ample supply of spare parts, was purchased from Gorham Model Products, Thousand Oaks, CA. Purchasing was selected over manufacturing due to time delay, cost, and other complications involved in attempting to build a helicopter at NPS. The unassembled *Hummingbird* arrived in boxes at NPS in 1992, and [Ref. 1] details the process and criteria by which it was chosen over other candidates.

Once the helicopter was assembled and modified as delineated in [Ref. 2], the tasks established for this thesis were the final design and modifications to initiate:

1) Constrained flight testing in a tethered condition

2) Untethered flight testing in a hover

3) Investigation of the *Hummingbird*'s flight envelope.

Figure 1 presents a graphical roadmap of the elements required to satisfy the final of objective of flight.

The first step towards continued static testing required development of a suitable and permanently dedicated test stand for RPH/RPV use. The original equipment and the modifications for use with the *Hummingbird* are detailed in Chapters III and IV.

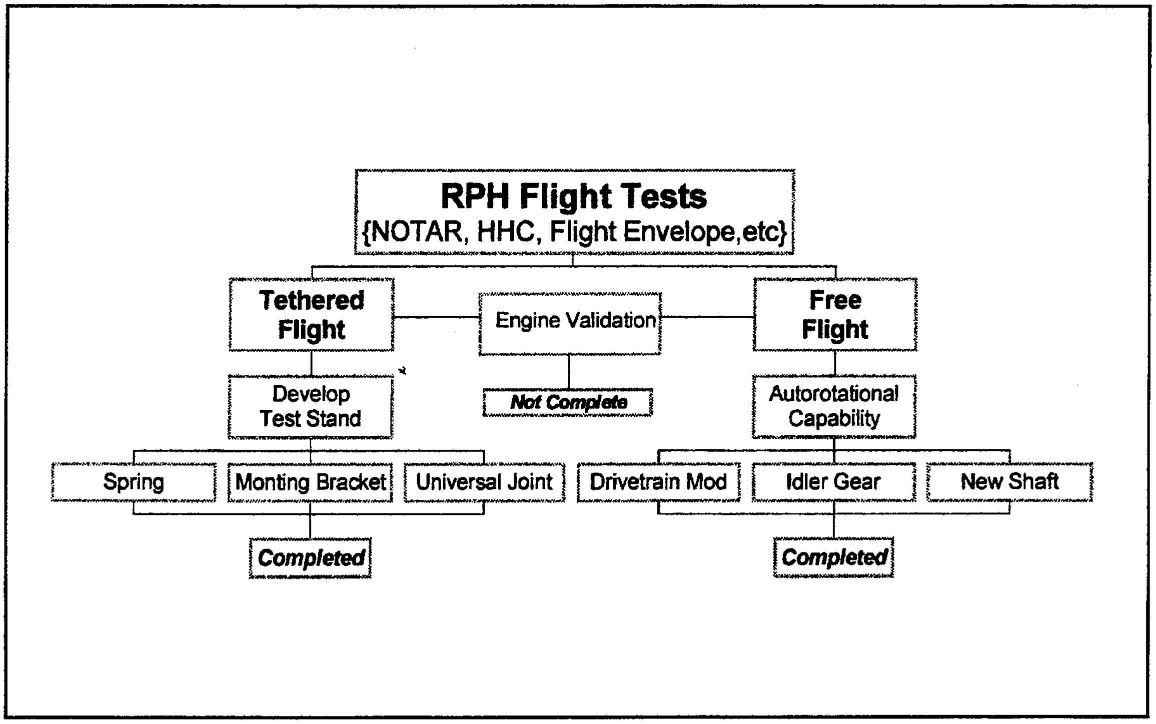

Figure 1. Roadmap of Objectives Prior to Flight

Early in the program, mechanical seizure of the installed engine occurred during engine validation tests. Inadequate engine cooling was suspected as the probable cause. Because of this, the thesis objectives were modified to encompass a revised engine validation program. Due to this mechanical seizure, the planned flight tests were not possible. Instead, a further modification of the helicopter's drivetrain and a break-in of the replacement engine would be required prior to the *Hummingbird's* first flight. The engine break-in consisted of mounting the engine on a test stand, and running it with an airplane propeller attached as a test load.

As noted in [Ref. 2], an additional shortcoming of the helicopter's design was a lack of autorotative capability. As one of the thesis tasks, modification of the drive system was undertaken to provide this capability. Autorotation allows the main rotor to continue turning in the event of an in-flight engine failure. This capability will greatly increase the survivability characteristics of the RPH in-flight .

Several of the conclusions and recommendations for [Ref. 2] were addressed and the generation of additional recommendations in the areas of rotor dynamics, instrumentation, and technical support are presented. The goal is research in areas such as NOTAR®, HHC, rotor dynamics, and rotor noise which will significantly benefit the NPS rotorcraft program for years to come. Figure 2 is a photograph of the fully assembled helicopter.

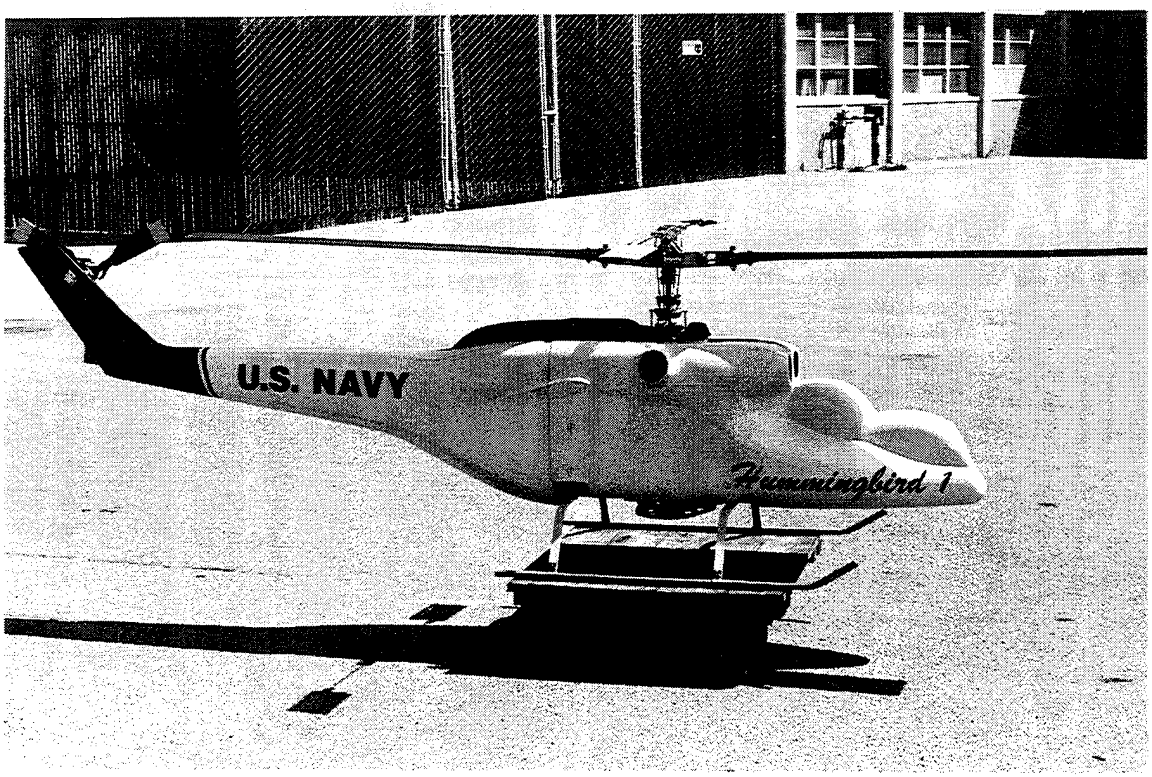

Figure 2. Fully Assembled *Hummingbird* RPH

II. BACKGROUND

A. WHAT IS AN RPH / RPV AND WHY USE ONE?

In simplest terms, an RPH is a remotely controlled helicopter that does not carry a pilot. Other commonly used names for RPH / RPV's are Unmanned Air Vehicle (UAV) and Radio-Controlled (R/C) aircraft. Reasons for wanting an RPH may include vehicle size restrictions, the operating environment's dangers to a live passenger, or the dangers associated with the flight envelope in which the aircraft will operate.

The purpose for wanting to test either a full scale or a smaller scale vehicle is to determine information about the aircraft. Areas of study include, but are not limited to, basic aerodynamic characteristics (lift, drag, thrust), dynamic response to forced inputs (either in the aircraft as a whole or in individual components), and aircraft sensor performance (avionics).

For experimental purposes, there are many benefits to using a scaled-down version of an aircraft. The most obvious advantage is safety and cost. For example, a one-quarter scale model of a helicopter requires a smaller testing area (either in terms of wind tunnel size or a test pad), along with smaller support equipment for maintenance and storage. The size and complexity of measurement devices are also reduced when compared to a full-sized aircraft. In general, the smaller the equipment (specifically the engine), the less cost to operate. Also, the dangers to the experimenters, the equipment and the general public can be minimized due to a more controlled environment.

B. PREVIOUS WORK

The decision process leading up to the procurement of the *Hummingbird* is covered in [Ref. 1]. The details of assembly and preliminary modifications for initial testing are outlined in [Ref. 2]. Research in areas such as No Tail Rotor (NOTAR®), Higher Harmonic Control (HHC), and general rotor dynamics have also yielded several theses [Ref.'s 3,4 and 5]. A computer program that models and predicts both rotor dynamics and performance of helicopters has also been generated by students from the Department of Aeronautics and Astronautics. The continually updated and improved program, called JANRAD (Joint Army/Navy Rotorcraft Analysis and Design) is written in the matrix-based MATLAB® software. This program has demonstrated accurate predictions that have been verified with actual rotor data with H-34 and UH-60A aircraft measurements, [Ref. 5]. The *Hummingbird* offers an excellent platform to continue to verify and refine JANRAD calculations.

C. TESTING FACILITIES

1. Location

The equipment used for testing the *Hummingbird* is located at the NPS Annex UAV Lab, residing on the grounds of the Navy Golf Course. Specifically, the UAV Lab occupies Building 214 and uses half of Building 230 for parts storage. There is an enclosed concrete pad, along with a blockhouse, situated directly behind Building 230 where tie-down operational testing is performed.

2. The Test Stand

The main equipment for testing is a hover fixture obtained from Naval Air

Weapons Center WD China Lake. This test stand was originally designed for testing the QH-50, a coaxial drone rotorcraft, in excess of 2500 pounds gross weight. The stand incorporates a universal joint on top of a piston that allows motion in all three axes. The helicopter may tilt freely in any direction, rotate around for a full 360 degrees and climb vertically for six inches of piston travel. The stand is secured to the concrete pad by four 0.5-inch diameter bolts. The stand required modifications to accommodate the *Hummingbird's* 150 lb weight and to restrict the range of motion of the universal joint. Also, a new mounting plate was required in order to safely secure the helicopter to the stand. These design improvements are discussed in detail in Chapter V. Figure 3 shows a drawing of the hover fixture before modifications.

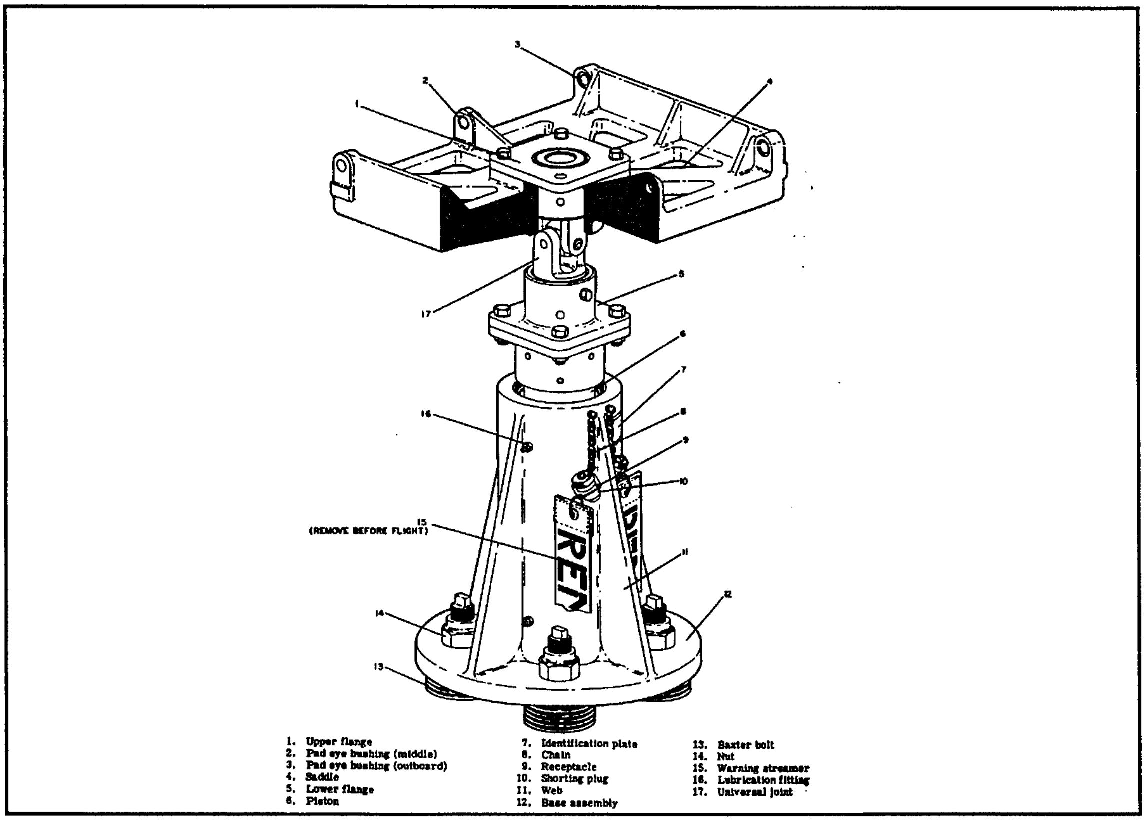

Figure 3. Hover Stand - Original Configuration

3. The Starting System

To start the aircraft, direct current electricity is required. Since a dc power supply cannot provide the necessary amperages to spin the engine and the connected rotors to a speed required for a self-sustained start, a power source consisting of two deep cycle marine gel cells, connected in series, was used to provide the amperage the system demanded. A spring-loaded toggle switch connected to a solenoid relay was used as the current controller. A compression release mechanism on the engine block prevented starter overheat once the engine delivered sufficient speed to power the rotors.

III. THE HELICOPTER IN AUTOROTATION

A. OPERATIONAL REQUIREMENTS FOR AUTOROTATION

The reason for the concern with autorotation is that a helicopter, unlike a conventional fixed wing aircraft, does not have the aerodynamic benefit of a set of wings that would allow it to glide in the event of engine failure. Instead, when the engine or engines are no longer driving the rotor system to maintain flight, the ability to effect a safe landing must come from the windmilling rotor system. For multi-engine helicopters, the simultaneous failure of all engines is extremely unlikely. In the event of a loss of one engine, the aircraft will be able to operate at a reduced power supply to the rotors and can also rely partially on autorotation. This may not allow the helicopter to maintain level or climbing flight, but the landing will be powered. For single-engine helicopters, once engine failure occurs, autorotation is the only possibility to safely land the aircraft with little or no damage. The ability of a single engine helicopter to effect a safe autorotation is possibly the single most important maneuver of which the rotorcraft is capable. Without the ability to autorotate, the helicopter and any passengers or equipment would likely be lost or permanently damaged. Figure 4 is a generic plot of operational combinations of altitude and groundspeed from which a successful autorotation could not be performed. This height-velocity diagram has also been known for many years as the "dead-man's curve" for obvious reasons.

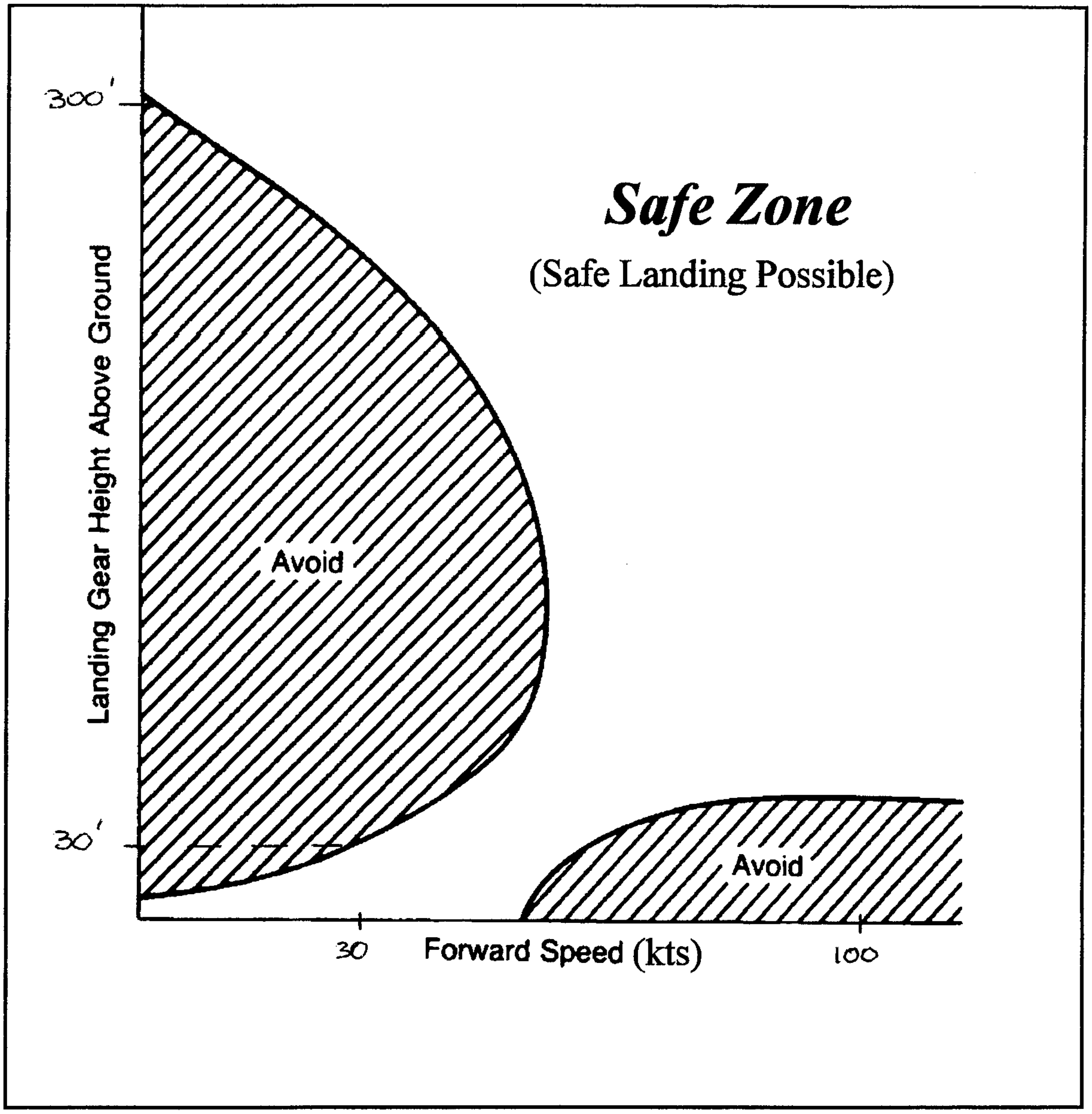

Figure 4. Height - Velocity Diagram for Single Engine Helicopter

At low altitudes and high groundspeeds, altitude is not sufficient to dissipate groundspeed for a safe flare and recovery. At higher altitudes with low speeds, the combination does not allow for enough time and rotor inertia build-up to adequately reduce the descent rate. The typical military operating environment falls frequently within the avoid areas.

B. HISTORICAL PERSPECTIVE

From the famous helix drawings of DaVinci to the autogiro of the early Twentieth Century, scientists, engineers and inventors have been fascinated with understanding and exploiting the regime of vertical flight. A list of some prominent figures in early helicopter history include Sir George Cayley, Thomas Edison, Rene Breuget, Dr. Heinrich Focke, Emile and Henry Berliner, Von Baumhauer, and Igor Sikorsky. These men concentrated their efforts in exploring powered vertical flight in machines that were the predecessors of modern helicopters. However, it is the work of the autogiro's founder, Juan de la Cierva, that is most applicable to autorotational flight.

The autogiro is a hybrid aircraft comprised of a conventional airplane and a free turning or unpowered rotor. This rotor provided a portion of the lift required for powered flight, but most importantly, allowed the aircraft to land nearly vertically and totally unpowered if necessary. Cierva was most concerned with eliminating the problems encountered in low-speed flight due to airfoil stall affecting conventional airplanes. The early designs of Cierva incorporated a rearward tilt of the rotor to generate lift as the air flowed from underneath the rotor when the autogiro was in forward flight. Later models of autogiros eliminated the need for conventional flight control surfaces (wings, ailerons, flaps) and relied on tilting the rotor disk to perform maneuvers. A tailplane was used for directional control and the propeller was also employed as the primary means for forward flight. Cierva was also the first to apply the principle of flapping rotors which had been suggested by Renard. The first fully-articulated rotor system was developed, also by Cierva, and lead-lag hinges were then added.

C. AERODYNAMICS OF THE HELICOPTER IN A HOVER

In a steady hover, the disk inscribed by the spinning rotors is what produces the lift forces necessary for the helicopter to remain aloft. In simplest terms, the thrust of the rotor system is equal to the weight of the helicopter, plus the airframe drag losses and mechanical inefficiencies of driving the tail rotor and auxiliary systems (typically between 10-15%). The airflow is accelerated from its inflow velocity at the rotor disk , v_1, also known as the *induced velocity,* to a remote wake velocity, v_2, which, in the case of hover, is about twice the magnitude of v_1. This result can be readily obtained using simple momentum theory. The theory can be determined from manipulation of either Bernoulli's equation or energy/momentum balances [Ref.'s 6 , 7, and 8]. The thrust which results from this momentum imparted to the airmass comes from the total change in kinetic energy of the airmass. The resulting thrust equation is:

$$T = 2 \rho v_1^2 A$$

Rearranging the thrust equation to solve for v_1 produces the term T/A. This is called the rotor's disk loading (**D.L.**), and has the units lbs/ft^2. The disk loading is a parameter that provides a measure of the hover performance of a rotor system. The lower the disk loading, the more efficient the lift system. That is, the greater the thrust that can be produced per horse power. When compared to other types of VTOL (Vertical Take-Off and Landing) aircraft, none can match the efficiency of the low disk loading helicopter. Typical D.L.'s for full-size helicopters range from 4 to 15 lbs/ft^2 . The *Hummingbird* has a disk loading of 1.75 lbs/ft^2.

D. AERODYNAMICS OF THE HELICOPTER IN AN AUTOROTATION

The autorotation, or the windmill brake state, is the condition of flight where the lifting rotor of the helicopter is unpowered and generates lift by the upward airflow through the rotor disk. This is shown in Figure 5, where the airmass velocity vector, U, has an upward flow instead of the downward direction seen in most other regimes of operation. Also seen in Figure 5, the parasite drag, D, acting on the airfoil, is overcome by the propulsive force acting on the airfoil. The propulsion results from the forward tilt of the lift vector, L, which results from reduced pitch on the blade, required to generate lift from the upwash on the rotor. We conclude that the helicopter's main rotor in autorotation is powered much like a windmill.

Eventually, the thrust produced by the rotor and the helicopter airframe drag counteract the descent rate, resulting in equilibrium, producing a controlled rate of descent. Symbolically, the thrust equation illustrates the flow reversal in the windmill brake state:

$$T = 2 \rho A (-V - v_1) v_1$$

For a graphical comparison, Figure 6 is included to illustrate the primary forces acting on an a helicopter airfoil in a climb. The climbing rotor has a lift vector (dL), which is tilted aft of the thrust line. Also, one can observe the downward airmass velocity vector u, which is comprised of the vertical velocity, V_V, and the induced velocity, v.

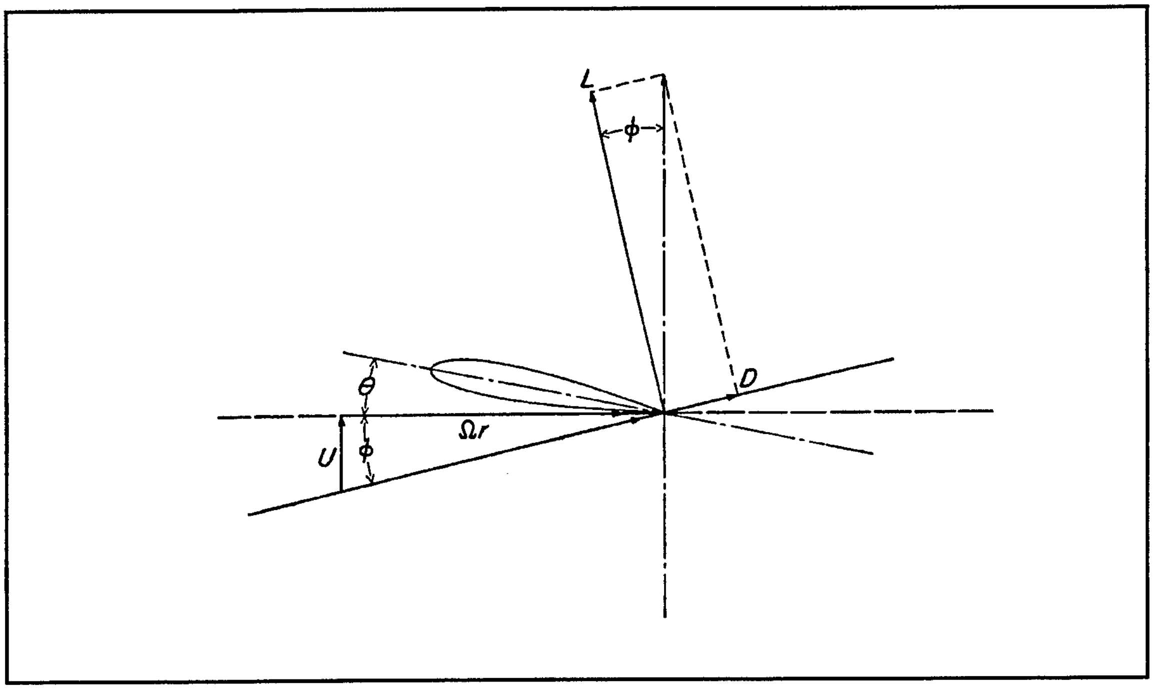

Figure 5. Blade Element in Autorotation

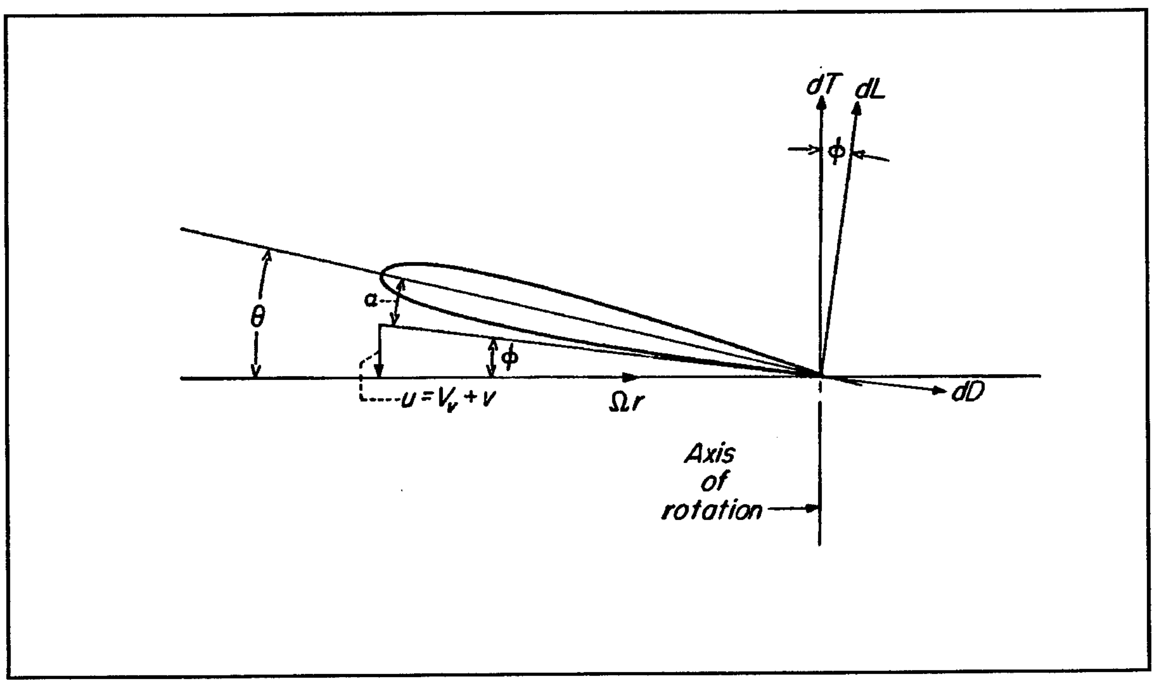

Figure 6. Blade Element in Climb

It can be shown that the lift created by the rotor system in autorotation is approximately the same as the resistance produced by a parachute of the same diameter as the rotor [Ref.'s 4, 5, and 6] . The helicopter's descent rate will be approximately twice the magnitude of the v_1 generated by a helicopter in a hover. The forward speed at which the minimum rate of descent occurs is the same as the airspeed for minimum power required.

Autorotation is begun by a reduction of collective pitch to a nominally minimum value. This maneuver reduces the individual blade angle of attack and consequently, reduces the induced drag of each blade, increasing the rpm of the system as a whole.

It is very important to note that the turning rotors are not engaged to the engine in an autorotation! The energy being generated by the windmilling rotor system is required for arresting the rate of descent at the conclusion of the maneuver. The engines and rotor system are isolated via a one-way bearing or sprague clutch mechanism that allows power transmission from the engine(s) to the rotors, but disengages when the rotors are not powered by the engine(s). Ideally, the transmission lubrication system will also be driven by the freewheeling rotors, but this may not be a necessary feature. Also, the tail rotor or NOTAR® blower system is essentially unpowered due to the absence of rotor torque requirements.

As mentioned in the preceding paragraph, airspeed is set for a minimum rate of descent or optimum glide path for a landing site (increasing the descent rate), to provide the maximum time to perform the maneuver. Rotor rpm can be maintained within desired limits through the varying of collective pitch. As expected, increasing collective pitch will increase the induced drag on the blades and therefore decay rotor rpm.

E. THE FLARE AND LANDING

Once the helicopter is established in a steady state descent (rapid as the rate may be), the need to arrest the speed at which the aircraft will impact the ground becomes paramount. A cyclic flare with constant collective pitch must be used to significantly slow the forward travel (groundspeed) and assist in arresting the rate of descent of the aircraft to allow landing within the structural limits of the landing gear/skids. The flare also increases the rpm of the main rotor to provide added rotor kinetic energy for letdown.

The final portion of the autorotation maneuver is to rotate the helicopter's nose attitude to a nearly level pitch attitude and a simultaneous smooth, strong increase in collective pitch to trade rotor rpm for lift from the blades. The increased lift will cause a significant and often rapid decay in rotor rpm, but the main issue is to slow descent rate to near zero at the point of impact with the ground. Figure 7 provides an excellent graphical illustration of the altitude, collective pitch, aircraft pitch attitude, groundspeed, rotor rpm, and descent rate versus horizontal distance traveled for a generic autorotation maneuver. See Appendix for a pilot's procedure for autorotation.

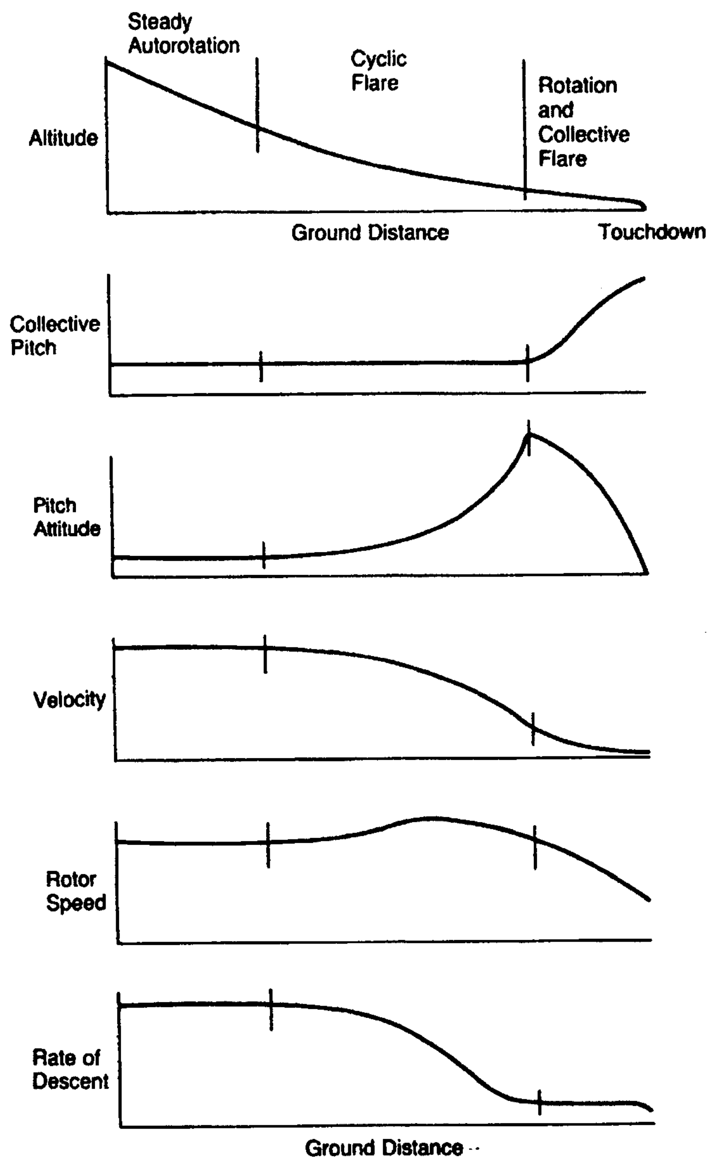

Figure 7. Autorotation Characteristics Timeline

IV. DEFICIENCIES FOUND

A. THE HELICOPTER

1. The Transmission

As noted in [Ref. 2], a primary design shortcoming from flight testing was the inability of the *Hummingbird* to autorotate. The preceding chapter discussed in detail the mechanics and the operational importance of autorotating, but the fundamental element is that autorotation is an aircraft-saving maneuver that every rotary wing aircraft should be able to accomplish. Furthermore, the ability to autorotate is ABSOLUTELY CRITICAL when the helicopter is powered by a single engine!

As built, the *Hummingbird* was unable to perform an autorotation due to the two-way transmission of power between the engine and the rotor system. A freewheeling clutch or similar mechanism was needed to enable the *Hummingbird* to autorotate.

2. The Engine

a. Engine 1

The first attempt at static testing revealed a deficiency with Engine 1 that was not readily apparent upon visual inspection of the *Hummingbird.* This engine suffered a mechanical seizure from overheating, after only ninety seconds of operation. The problem of overheating was identified by Gorham Model Products, as evidenced by the cooling fan and cowling inside the body of the helicopter that were post-design additions. These additions were likely employed to dissipate the heat when the helicopter was not in forward flight. Contained within the Weslake Aeromarine Engines Operators

Handbook [Ref. 9], is a note that specifically cautions:

> The engine is aircooled and must not be run in static conditions unless an adequate cooling airflow is supplied. Maximum cylinder head temperatures must not be exceeded.

As a result of its mechanical failure, Engine 1 became a parts cannibalization source.

b. *Engine 2*

The second engine had been unused when pulled out of the shipping box. Auxiliary equipment, such as the compression release mechanism and the carburetor, was not installed. This engine required installation of the auxiliary components, plus a means to apply a load during the break-in. Breaking the engine in while fully installed in the helicopter was not desired, in lieu of the mechanical failure of Engine 1. Thus, an engine test stand plus test load were needed. Also, a starting assembly for Engine 2, while attached to the test stand, was required since the starting system for an engine installed in the *Hummingbird* could not easily be adapted for use with the engine test stand.

B. THE HELICOPTER TEST STAND

The purpose of the helicopter test stand was to provide a secure device on which the *Hummingbird* could be mounted for static testing. The universal joint located on top of the piston would allow motion in all three body axes (roll, pitch and yaw), and also allow six inches of vertical travel. The pitch and roll axes would move around the universal joint, while yawing axis would occur as the piston rotated in its sleeve.

1. The Universal Joint

The universal joint of the test stand duplicates the range of motion created by a ball and socket joint. The joint provided very little resistance and large amplitude to the helicopter's tilting when the *Hummingbird* was mounted on the stand. This was not a desirable feature in the preliminary stages of static testing, since the aircraft could possibly be faced with a 45 degree (pos/neg) or greater pitch attitude or a roll angle.

2. The Mounting Plate

As seen from Figure 3, the original test stand was fitted with a large aluminum mounting bracket that weighed over 20 pounds. The mounting plate lacked an adapter that would easily allow the *Hummingbird* to be securely fixed to the test stand. Also, any additional mounting hardware would add even more weight to what was already present on the piston, making it more unlikely that the helicopter would be able to lift its own weight and that of the piston-mounting bracket assembly. A requirement developed to manufacture a mounting mechanism that would allow the *Hummingbird* to be secured on the stand without any significant weight penalty.

3. The Piston

The piston provides for up to six inches of vertical travel of the helicopter when affixed to the stand. Unfortunately, the combined weight of the piston, the universal joint and the mounting bracket would add an additional 65 pounds to the weight of the helicopter that the rotors would need to lift. The external load lift capability of the *Hummingbird* was approximately 40 pounds, so some method was needed to alleviate or compensate for the weight of all components of the stand and make the weight of the helicopter and the power required for directional control (tail rotor) the only demands on the engine.

C. THE TEST PAD

The test pad is a concrete area, 24 feet long by 17 feet wide, located behind Building 230. The pad is a fenced enclosure, with the blockhouse located outside the northwest corner. The pad required some means to firmly secure the test stand to the concrete and a higher fence to afford greater protection to golfers when the helicopter was in operation.

V. SOLUTIONS TO DEFICIENCIES

Low cost and relative ease of implementation were the driving factors behind all potential solutions to the deficiencies found in Chapter IV. Since time was a major factor, the availability of parts and possible delays incurred through the manufacture of parts vice procuring off-the-shelf items were also heavily weighed.

A. THE HELICOPTER

1. The Transmission

The installation of two unidirectional roller clutches inside an intermediate gear of the transmission addressed the helicopter's inability to autorotate. To most closely fit the 34 mm height of the gear, two clutches (with an outer diameter of 24.00 mm, an inner bore of 18.00 mm and a height of 16.00 mm, ordered from Sterling Instruments [Ref. 10]), were needed. One-way roller clutches work in the following manner: The rollers grip the shaft when driven in one direction. This occurs when the engine is trying to drive the rotor system. However, when the gear is spinning due to the freewheeling rotors and not due to the engine, the rollers will not grip the shaft. This disconnects the rotors from the engine and allows for autorotation.

First, the bore for the gear was enlarged, from an inner diameter of 19.00 mm to 24.00 mm to accommodate the roller clutches. The roller clutches were then pressed into place. Next, a new shaft was manufactured, since the original shaft had keyways cut on both sides. The new shaft needed to have a smooth exterior surface for the length of the shaft that was to rotate inside the one-way bearings. The original shaft had a nominal diameter of 19 mm for its entire length. The new shaft was required to have a 19 mm diameter for the first 50.8 mm of length, while the remaining length required an 18 mm diameter in order to properly fit inside the needle bearings. Finally, a bushing was made to fit inside the top bearing of the gear's housing bracket to account for the difference in shaft diameters from the original shaft to the new one.

The following pages contain photographs of various elements of the transmission system. Figure 8 is the entire assembled transmission layout. The shaft pointing to the left is the tail rotor driveshaft. Figure 9 shows both the original shaft (above the ruler) and the autorotation shaft. Figure 10 depicts the original gear with the center bore enlarged and the autorotation bearings already installed. Figure 11 depicts the large gear that drives the autorotation shaft when the engine is operating, the new shaft, the intermediate gear that houses the sprague clutch bearings, and the gear housing with the bushing installed. Figure 12 shows the autorotation shaft, intermediate gear, and housing, fully assembled.

Another key feature of the new transmission was that the tail rotor would continue to be driven by the freewheeling rotors. The inherent advantage to installing the unidirectional clutch in the gear that was chosen over other elements of the transmission was that directional control of the helicopter in an unpowered descent is maintained.

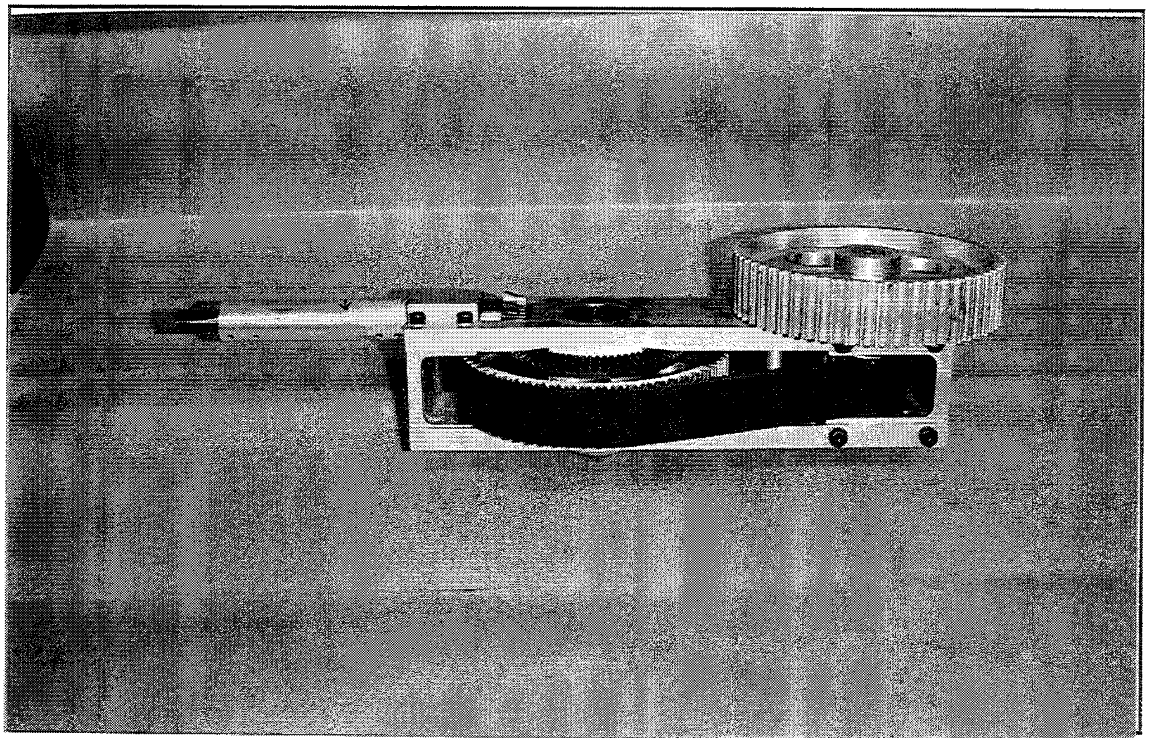

Figure 8. Fully Assembled Transmission with Tail Rotor Driveshaft

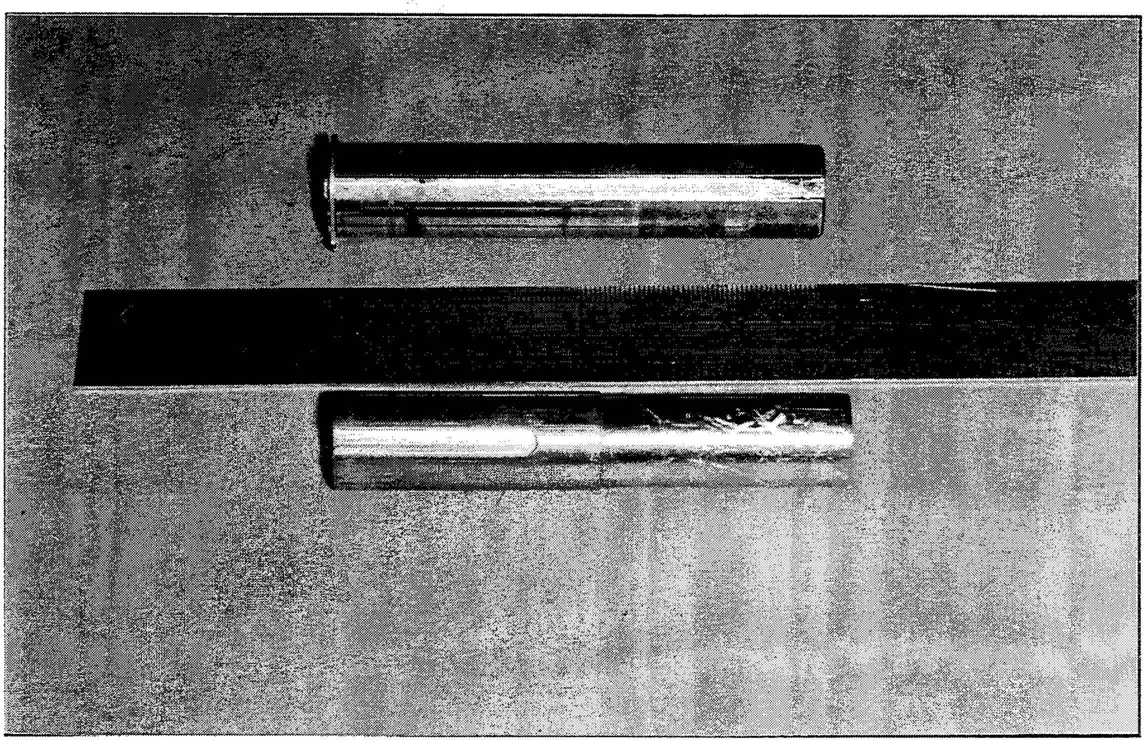

Figure 9. Original Shaft (top) and Autorotation Shaft

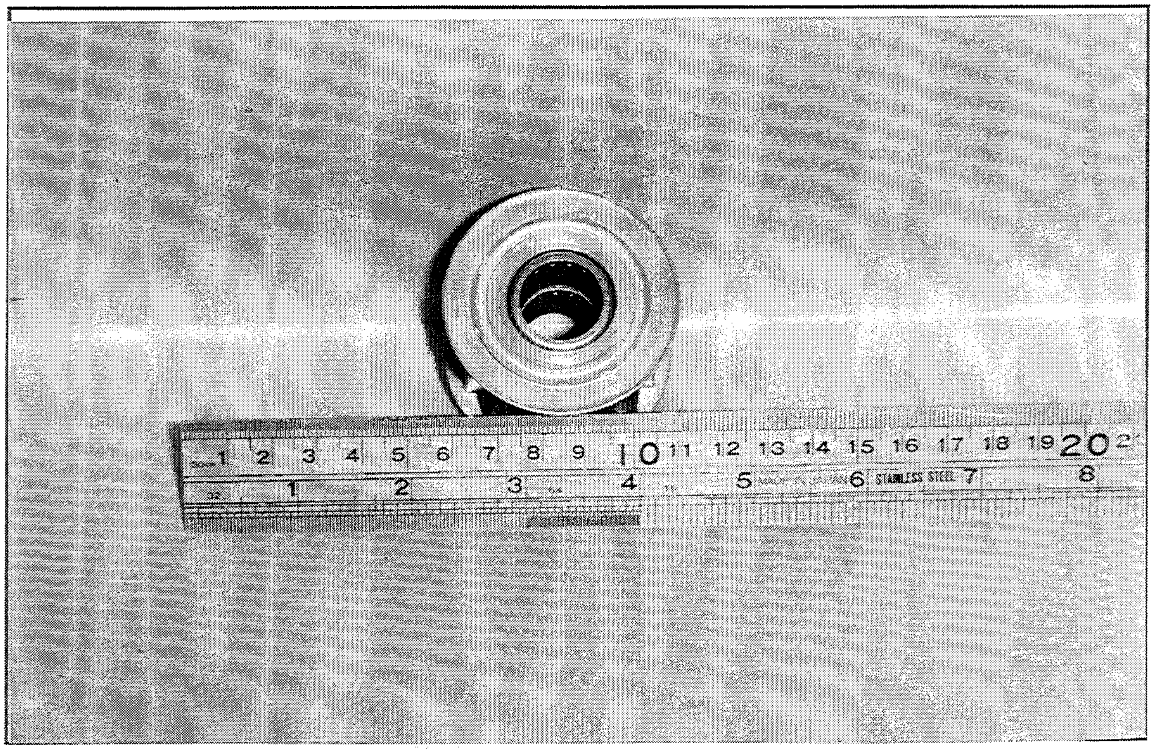

Figure 10. Intermediate Gear with Sprague Clutches Installed

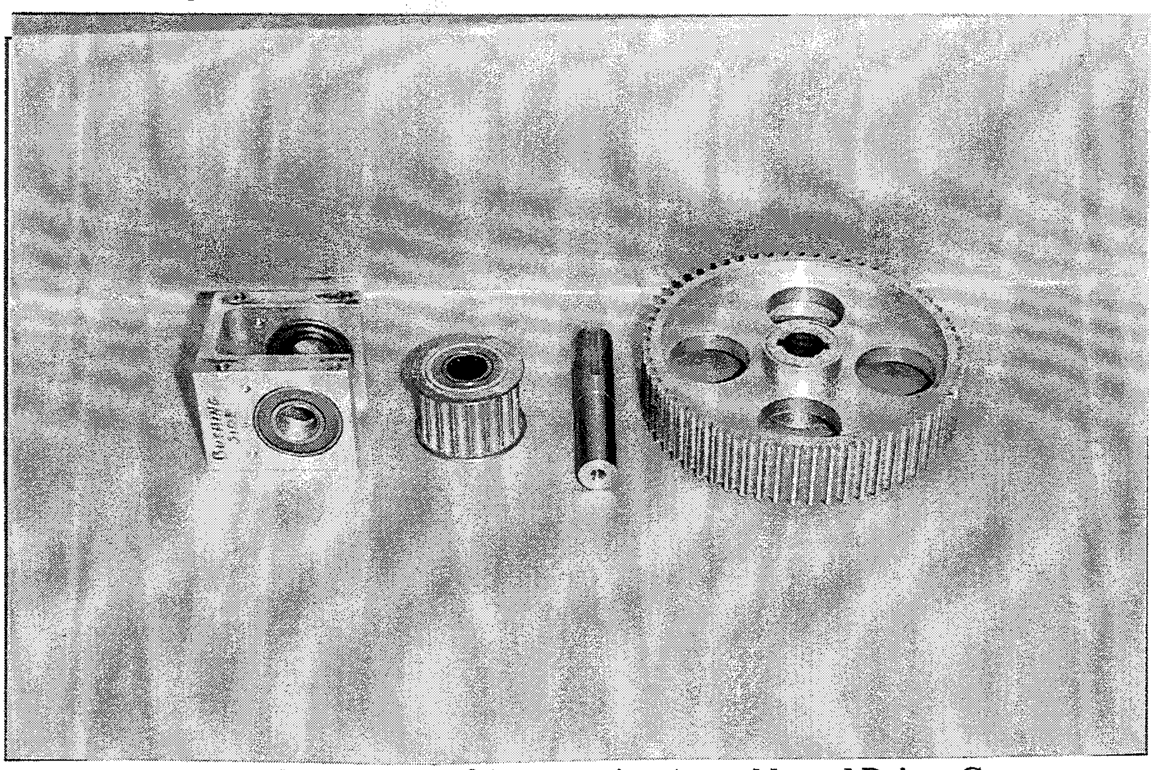

Figure 11. Components of Autorotation Assembly and Driver Gear

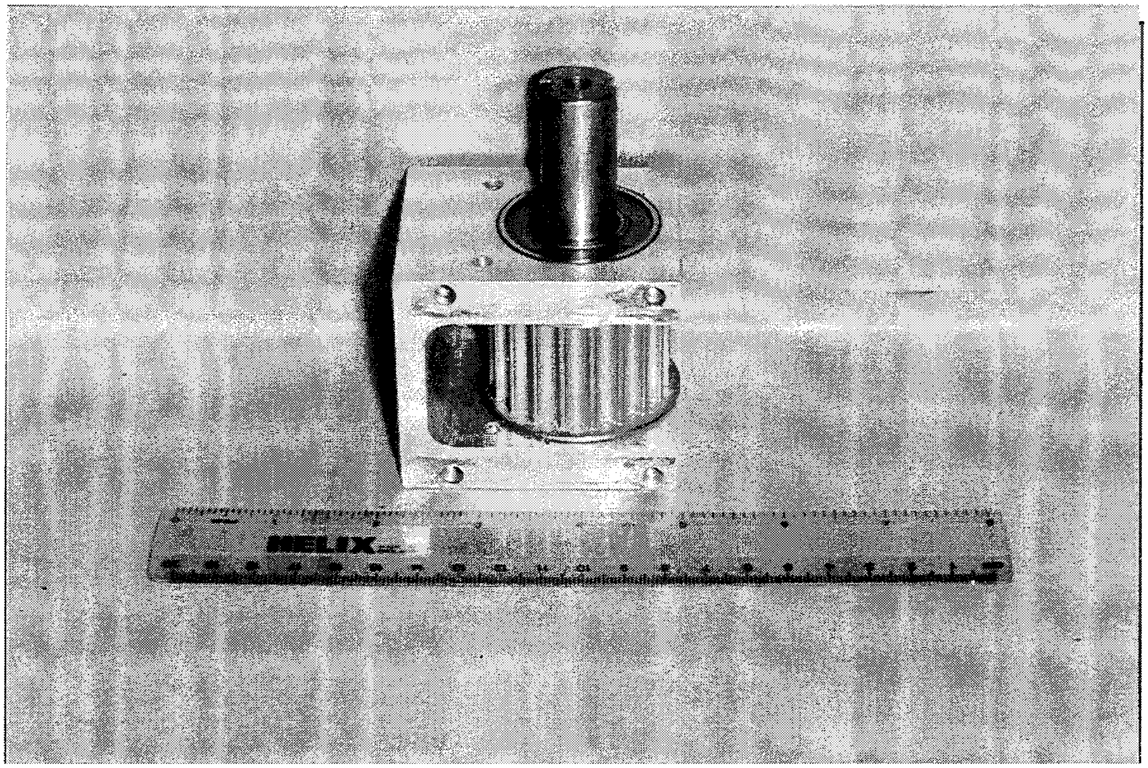

Figure 12. Assembled Autorotation Components

2. Engine 2

Engine 2 was mounted on an engine test stand located in the blockhouse behind Building 230. To provide a working load on the engine during break-in, a 30-inch diameter birch propeller commonly used for ultralight aircraft was purchased. This propeller (purchased from Aircraft Spruce Specialty Corporation, Fullerton, CA [Ref 11]) was sized in accordance with power and speed parameters listed in the specifications found in [Ref. 9]. Figure 13 is a photograph of Engine 2, with propeller, mounted on the engine test stand. The power source for the test stand starter system was the marine gel cells used for starting the helicopter.

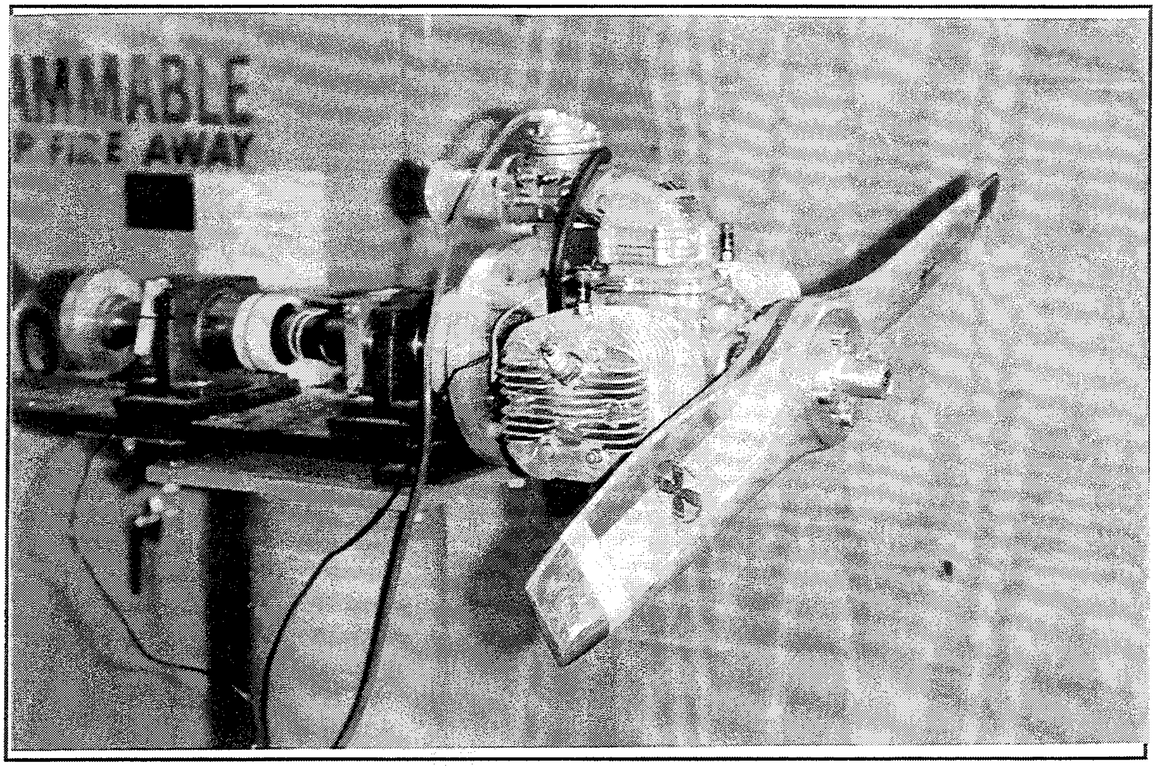

Figure 13. Engine 2 on Test Stand with Propeller

B. THE TEST STAND

1. The Universal Joint

In order to limit the range of motion of the joint, a four-inch diameter section of 1/32-inch thickness PVC pipe was fastened around the joint. The pipe was cut longitudinally so that a variable-geometry brace, held together by two circular clamps, could allow for as much or as little freedom of movement as desired. Figures 14 and 15 depict the universal joint brace components and the universal joint with brace attached.

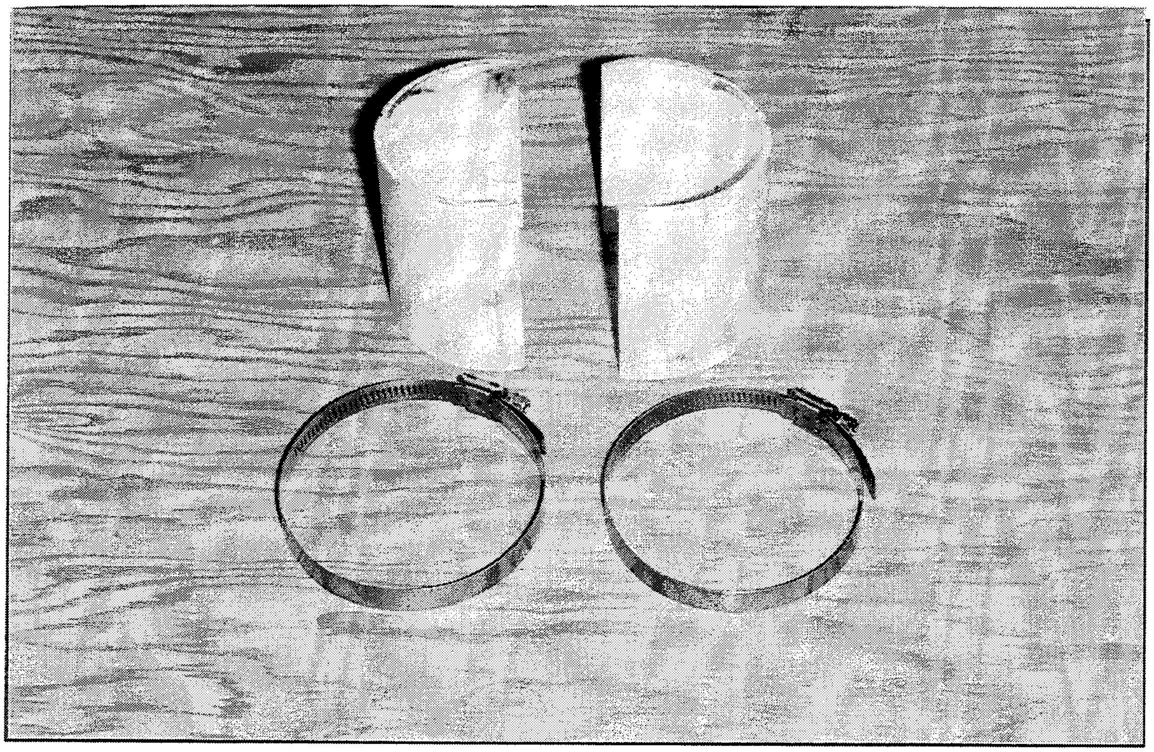

Figure 14. Restrictor Bracket for Universal Joint

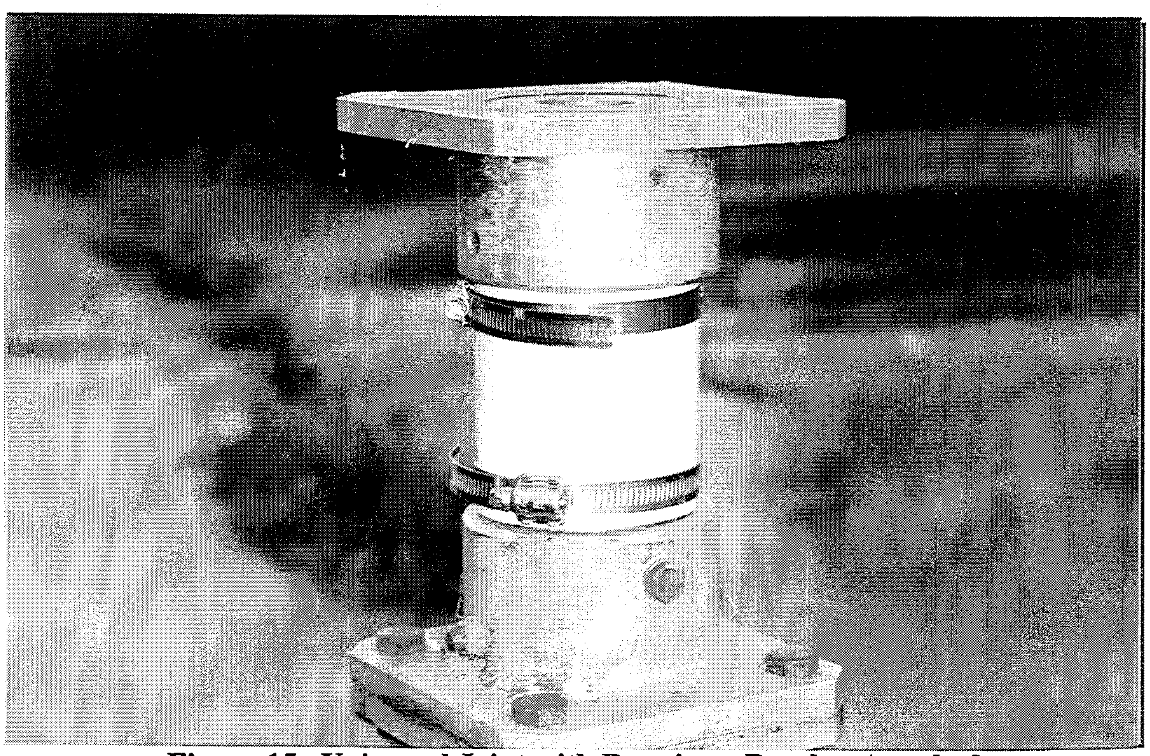

Figure 15. Universal Joint with Restrictor Bracket Attached

2. The Mounting Plate

The original mounting bracket was removed as a first step towards finding a lightweight new mounting system for securing the *Hummingbird* to the test stand. In its place, a rectangular plate of 1/8-inch thick aluminum was cut. This plate, comprised of ALCOA 7075 aluminum, was chosen for its relatively high strength-to-weight characteristics and ready availability. The *Hummingbird* was fastened to the plate by four 1.25-inch diameter x 3.0-inch long U-bolts, which hold the helicopter landing skids. The total weight of the plate and U-bolts was just under 15 pounds, which resulted in a weight savings of approximately 10 pounds.

3. The Piston

In order to alleviate the need for the Hummingbird to lift not only its own weight, but also the approximately 65 pounds from the combined weights of the piston, universal joint, and mounting platform, a compression spring was designed and ordered from Coil Springs Specialty. Made from 0.25-inch diameter piano wire and delivering a spring rate of 65 pounds of force per inch, the spring has a maximum external diameter of 2.5 inches, which allows it to fit inside the bore of the piston. The spring has a length of 24.5 inches relaxed, and will compress to 18 inches to accommodate the piston's entire length of travel.

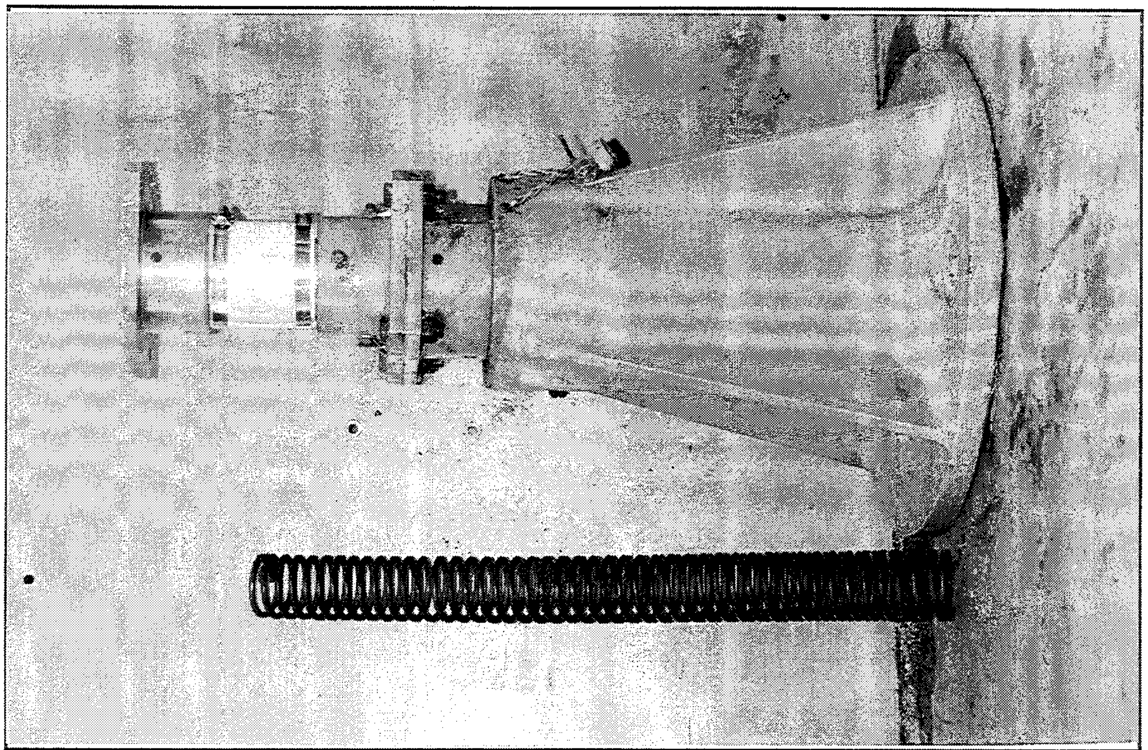

Figure 16. Hover Stand with Piston Spring

C. THE TEST PAD

In the interests of safety to both the experimenters and the frequent golfers traversing the area near the test pad, a three-foot extension to the six foot high chain link fence surrounding the test pad was incorporated. The extension was needed due to the height of the Hummingbird's spinning rotors, while attached to the test stand, exceeding the top of the original fence. While the likelihood of a dynamic component departing the aircraft and endangering anyone was extremely small with the original fence height, it was felt that, in the interests of all parties concerned, adding a larger factor of safety to the operating area was nonetheless desirable.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The *Hummingbird* RPH is an aircraft that provides the Naval Postgraduate School with an outstanding research platform for a variety helicopter studies for many years to come. For the *Hummingbird* itself, the redesign and implementation of a unidirectional roller clutch system in the transmission produced an autorotation capability that was a critical shortcoming in the original design and manufacture. As illustrated by the detailed information describing the importance of autorotation, the survivability of the helicopter was greatly enhanced.

The improvements to the test stand, including the mounting platform, universal joint restrictor, and weight-compensating spring provide the Department of Aeronautics and Astronautics with an invaluable piece of test equipment for RPH/RPV research that it did not previously possess. Also, the overall safety of experimenters and golfers in the immediate vicinity of the test pad behind Building 230 was increased through the installation of a fence extension surrounding the pad.

This thesis had the final modifications to the NPS *Hummingbird* in preparation for flight as its both its title and objectives and these goals have indeed been met. With additional benefits in the areas of equipment and safety to future RPH/RPV research resulting from the work on this thesis, the Department of Aeronautics and Astronautics at the Naval Postgraduate School is in position to continue its leadership in UAV projects and study.

B. RECOMMENDATIONS

Although many of the recommendations of the previous thesis were addressed in this work, there are still several areas in which both the *Hummingbird* itself and the support facilities can be improved.

1. Recommendations for the *Hummingbird*

a. Ensure adequate cooling for engine

The seizure of Engine #1 to overheating was a nearly devastating loss to the RPH project. While Engine #2 has been installed on the test stand and broken in with extreme care, the issue of overheating while the engine is installed in the helicopter has not been fully examined. Measurement of engine exhaust temperatures and instrumentation to monitor the engine temperature would be a large improvement in evaluating operating regimes. A better form of forced cooling for the engine while installed in the *Hummingbird* should be examined.

b. Design and Manufacture Horizontal Stabilizers

As currently configured, the aircraft is capable of hovering and very low speed forward flight due to a lack of horizontal stabilizers. There are already mounting points on the tailboom and a sensible sizing trend analysis would provide an excellent starting point for these critical flight surfaces. By designing and installing a set of horizontal stabilizers, the entire forward flight regime could be explored.

c. Install and Test NOTAR® Boom and Blower System

While a NOTAR® boom has been built and tunnel-tested, an effective system to provide and properly control the air required for the yaw axis has not been designed or implemented. The use of NOTAR® technologies is a very exciting area of helicopter control and should not continue to go neglected. The recent close cooperation between NPS and McDonnell Douglas Helicopters should produce a symbiotic relationship in which the Hummingbird, configured with a NOTAR® directional control, could play a major role. To this date, there is not a known RPH in operation with a NOTAR® system, thus providing a NOTAR®-equipped *Hummingbird* a unique place in RPH experimentation.

d. Full Instrumentation of a Rotor Blade

As mentioned in Reference 2, the lack of a three-bladed main rotor system precludes further research into HHC. However, in the absence of a three-bladed system, valuable dynamic data could be obtained from instrumenting a blade. Currently there are no rotor blades or rotor systems at NPS that are fully instrumented.

e. Incorporation of Hummingbird Data into JANRAD

Another project that would benefit from instrumenting a blade is a modeling the Hummingbird in JANRAD. The opportunity to physically validate JANRAD in its current configuration, along with the direct experimental feedback that future elements of the program would require, would greatly expand the utility of software generated on site. This would be an asset that few academic institutions could match.

2. Recommendations for RPH/RPV Support

While the facilities and support equipment of the UAV Lab, especially the technician support, was generally outstanding, there was one glaring shortcoming that needs attention. That area was for an access-controlled site at which to operate needs attention. That area was for an access-controlled site at which to operate RPH/RPV's. Currently the use of a R/C Club airfield located in Chular is the only reasonable option within 100 miles of NPS. The drawbacks from this facility include the inability to keep anyone not associated with NPS excluded from the site during testing. The potential dangers to non-NPS personnel, especially from a safety standpoint, make this a pressing issue as the Hummingbird progresses towards free flight.

APPENDIX. PILOT'S PROCEDURES FOR AUTOROTATION

The first inclination one has of an impending autorotation is either a definite change in the engine noise (a winding down), or a rapid decrease in the rotor rpm (N_r) observed on the gauge. As all rotary wing pilots are automatically conditioned to do, collective pitch is then immediately reduced to minimum. This procedure is commonly known as "bottoming the collective". The next two items usually occur simultaneously. The nose attitude of the helicopter is raised or lowered to attain a minimum rate of descent airspeed (minimum power required on the "Bucket Curve"), and a proposed landing site is selected. The alignment of the aircraft's flight path is then examined with respect to the windline (best results are obtained for slowing groundspeed when the helicopter is pointed with the wind on the nose), and a turn is initiated if altitude permits. Also occurring at this time is a very quick performing of an immediate landing checklist and a radio "mayday" call.

The final element of the autorotation is also the most difficult. Once the flare has reduced groundspeed to the desired level and the helicopter is in a near vertical descent, the pilot is no longer flying on his gauges and must look outside the cockpit to best determine the point at which he must "pull and level". The strong upward collective will provide whatever cushioning is possible for the landing and the level nose attitude allows the landing gear to bear the brunt of the impact. This sudden change in torque on the rotor shaft will also cause a directional change, and appropriate pedal must be applied to continue pointing the nose in the direction the helicopter is traveling.

Practicing autorotations is something that a pilot performs hundreds or thousands of time in his career, but the only one that truly counts is when the emergency is a real one and the engines are not coming back for a wave-off. The damage or loss of the aircraft and/or injury to the passengers or cargo are the reality of the autorotation and every pilot knows it each time he practices this critical maneuver.

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